minority carriers. This can be considered by adding a linear term to equation (20.68). Thus

$$I_{SC}(G, T_c) = I_{SC}^* \cdot \frac{G}{G^*} \cdot \left[1 + (T_c - T_c^*)\frac{dI_{SC}}{dT_c}\right] \tag{20.73}$$

where the temperature coefficient dI_{SC}/dT_c depends on the semiconductor type and on the manufacturing process, but it is always quite small. Typical experimental values are below 3.10^{-4} (A/A)/°C [51, 59]. For a solar cell operating at 70°C, that represents only 0.13% of I_{SC} increase. Hence, ignoring this dependence has no practical effects, in all the cases.

The open-circuit voltage tends to increase with the illumination level. The ideal diode equation (see equation (20.60)) shows there is a logarithmic dependence. Then, this effect can be considered by adding a logarithmic term to equation (20.69). Thus

$$V_{OC}(T_c, G) = V_{OC}^* + (T_c - T_c^*)\frac{dV_{OC}}{dT_c} + V_t \cdot \ln\left(\frac{G_{eff}}{G^*}\right) \tag{20.74}$$

Note that the relative influence of this new term increases with decreasing irradiance. For example, for $G_{eff} = 500$ W/m^2 and $G_{eff} = 200$ W/m^2, it represents about 3 and 7%, respectively. Hence, its importance when predicting the energy delivered by PV modules depends on the irradiance distribution of the irradiation content. Obviously, it is more important for northern than for southern countries. For example, in Freiburg-Germany ($\phi = 48°$) about 50% of yearly irradiation is collected below 600 W/m^2 and 18% below 200 W/m^2. Meanwhile in Jaen-Spain ($\phi = 37.8°$) about 30% of yearly irradiation is collected below 600 W/m^2 and only 6% below 200 W/m^2. Moreover, it should be understood that very low irradiances are sometimes rejected by PV-system requirements. For example, in grid-connected systems, DC power from PV modules must be large enough to compensate for the inverter losses. Otherwise, the PV system becomes a net energy consumer.

While this logarithmic term does account for some variation in open-circuit voltage as irradiance changes, it does not adequately predict the rapid decrease observed at values of irradiance less than about 200 W/m2, which causes a noticeable efficiency decrease below this value. The use of a second logarithmic term has been proposed [60] to also consider this low irradiance effect. Thus

$$V_{OC}(T_c, G) = \left[V_{OC}^* + \frac{dV_{OC}}{dT_c}(T_c - T_c^*)\right]\left[1 + \rho_{OC}\ln\left(\frac{G_{eff}}{G_{OC}}\right)\ln\left(\frac{G_{eff}}{G^*}\right)\right] \tag{20.75}$$

where ρ_{OC} and G_{OC} are empirically adjusted parameters. Values of $\rho_{OC} = -0.04$ and $G_{OC} = G^*$ have proven adequate for many silicon PV modules.

The sun spectrum shifts over time, due to changes in atmosphere composition, and changes in the distance the light has to travel through the atmosphere. This can affect the response of PV devices, especially if they have a narrow spectral response. Martin and Ruiz have proposed [61] a model based on the parameterisation of the atmosphere by means of the clearness index and the air mass, and this considers independently the spectrum of each radiation component: direct, diffuse and albedo. It can be described by